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TECHNICAL REPORT RD-SS-92-11

THE EQUIVALENT FLAT NOSE DIAMETER OF HEMISPHERICAL NOSE CYLINDRICAL PROJECTILES FOR IMPACT INDUCED DETONATION OF ENERGETIC MATERIALS

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The analysis of explosive detonation via projectile impact is inherently complex because of the many variables which must be considered. One very important variable is the nose or tip shape of the projectile which contacts the bare unprotected planar surface of the energetic material. This report demonstrates that Hemispherical Nose (HN) projectiles (cylindrical, rods, or spheres) are equivalent to a much smaller Flat Nose (FN) surface. This equivalence is suggested by comparison with appropriate theory and a very limited amount of experimental data for two explosives (PBX-9404 and COMP-B).

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I. INTRODUCTION

Analysis of shock induced explosive detonation via general projectile impact is complicated not only by impact velocity (V_I), projectile material, length, and cross–sectional area requirements but by projectile nose shape as well. The simplest nose shape from an analytical viewpoint is flat (FN) or planar. A conical shape is next in complexity, followed by the hemispherical (HN). Many projectiles while penetrating armor and/or cover plates will erode and acquire essentially a hemispherical profile. Consequently, the hemispherical shape is important from academic and practical considerations.

An earlier analysis of experimental data for impact shock induced detonation via FN cylindrical projectiles is documented in Reference 1. In this work, some simple empirical relations were derived which are functions of the projectile cross–sectional area and known impact shock variables. These relations were introduced to enhance and/or supplement current empirical detonation prediction methodology.

It is the purpose of the present report to demonstrate that for detonation of one explosive (PBX–9404), the HN shape is equivalent to a much smaller FN shape at the same impact velocity (V_I). The demonstration is accomplished by comparing theoretical and experimental information. It is shown that the equivalent flat nose diameter (D_{FNEQ}) of a HN projectile (D_{HN}) is:

$$D_{FNEQ} = \left(\frac{V_I}{U_{SP}}\right) D_{HN} \tag{1}$$

where:

U_{SP} = Shock front velocity in the projectile(steel).

A very limited amount of experimental data was available for the COMP–B explosive. This datum (one point) compares favorably with the above relation when a reasonable extrapolation of FN experimental information is performed. These experimental data are discussed more thoroughly in Section II.

References 2, 3, and 4 also contain analyses of hemispherical nose projectile impact shock induced detonation of explosives. The general emphasis and scope of these documents differ somewhat from that of the present report.

Here, the thrust is to delineate the flat nose equivalent diameter (D_{FNEQ}) of HN shapes. This is important, since when D_{FNEQ} is found from Equation 1, then it can be employed for the diameter, D, in the empirical relations described in Reference 1 for FN projectiles. If equivalence actually exists, then there should be correlation with the FN projectile relations in Reference 1. Two examples of this type of correlation are given for the Held explosive sensitivity parameter, $V_I \sqrt{D}$, and the comparison is satisfactory.

II. EXPERIMENTAL INFORMATION

Reference 1 contains a rather detailed analysis of five sets of experimental impact induced detonation data for five different secondary explosives. These data from diverse sources had been systematically acquired by firing flat faced projectiles with different cross–section area and different velocities (V_I) into flat explosive specimens.

The basic result of these experimental investigations was that the impact velocity (V_I) necessary to cause detonation was highly dependent on the projectile cross–section area dimensions or rod diameter (D_{FN}). Some of these data from Reference 5 for PBX–9404 are shown in Figure 1 (V_I versus D_{FN}). The line shown is the boundary between detonation and no detonation. Detonation occurs for points above the line and does not occur for points below the line. Detonation occurred for the six points illustrated, so the demarcation line shown is conservative (Detonation always occurs for points above the line).

Reference 5 also contains similar experimental information for PBX–9404 subjected to impact by steel cylinders with hemispherical tips. The diameter (D_{HN}) and impact velocity were systematically varied to ascertain the demarcation limits. This information is also shown in Figure 1. Detonation occurs for all the points shown except one, which is denoted by a dark or filled–in symbol. The faired demarcation line goes between the "NO GO" point and the nearby "GO" point and passes through or above the other "GO" points. Thus, it is believed to be conservative.

Reference 6 contains experimental information for the detonation demarcation limits of PBX–9404 and COMP–B when struck by a spherical steel projectile. Only one diameter (1.3 cm) was employed but the striking velocity was varied to define the critical velocity, V_{CR}, for each explosive. Examination of Figure 2 in Reference 6 reveals the following critical velocities where detonation was certain to occur:

Explosive	V_{CR} (Km/sec)
PBX–9404	1.14
COMP–B	1.75

This "GO" point for PBX–9404 is plotted in Figure 1 where it agrees closely with the information from Reference 5 for the hemispherical tipped cylindrical rod projectiles. This is interesting since it illustrates the importance of nose shape as contrasted to the overall shape (rod or sphere). Apparently the length of the sphere (its diameter) is large enough so that reflected tensile stress waves from the rear do not diminish the main compressive pulse magnitude (P_S) before a critical amount of time (T_{CR}) has elapsed. See Reference 1 for additional information concerning for the importance of the compressive shock pulse duration (T_{CR}).

The steel spherical projectile "GO" point for COMP–B is shown in Figure 2. No information for hemispherical tipped cylindrical tipped rod impact induced detonation is available for COMP–B. However, there is information for flat nose cylindrical projectile induced detonation available in Reference 7. Three critical experimentally derived data points (V_I, D_{FN}) from Reference 7 are shown in Figure 2 and this defines the detonation demarcation curve for COMP–B and flat nose cylindrical rod projectiles. Note the extrapolation of this demarcation line to a region of smaller D_{FN} and large V_I. This non–linear extrapolation is considered to be a reasonable representation of the detonation demarcation line in this important region. It was done so that an "experimental" value of D_{FNEQ} could be graphically estimated as shown in Figure 2 for the single data point of the spherical projectile striking COMP–B.

A similar example for PBX–9404 is illustrated in Figure 1 for one of the HN rod projectiles. For a given V_I which produces detonation, the hemispherical nose diameter (D_{HN}) has to be much larger than the corresponding flat nose equivalent diameter (D_{FNEQ}).

Thus, the hemispherical nose is not as efficient in producing detonation as a flat nose. In other words, a large portion of the HN projectile diameter (D_{HN}) is ineffective so far as impact shock induced detonation is concerned. Only a much smaller portion (D_{FNEQ}) is effective and it can be experimentally ascertained as described above and illustrated in Figures 1 and 2. Experimental values of D_{FNEQ} for the HN and spherical projectiles are given in Table 1.

The appropriate theory is discussed in the following section.

III. EQUIVALENT FLAT NOSE DIAMETER (D_{FNEQ})

The contents of Reference 1 delineate the importance of the projectile flat nose area for impact shock induced detonation. That is, an undisturbed plane or one dimensional shock pressure must act on a critical area (A_{CR}) for a specific amount of time (T_{CR}) or detonation will not occur. Both Moulard's critical area concept and the Walker–Wasley critical energy concept must be satisfied.

Thus, intuitively, it should not seem strange that only a portion of a hemispherical nose area (or diameter) would be effective for shock induced detonation. This would be "almost flat" part of the surface near the projectile centerline.

Reference 8 provides a relatively simple analysis which indicates how much of the hemispherical curved impacted surface would experience essentially an undisturbed or undiminished shock pressure pulse before a release or rarefaction (tensile stress) wave forms and propagates back into the shocked material. The rarefaction relieves the relatively high compressive shock pressure. The time and place of its occurrence influences the duration (T_{CR}) and area (A or A_{CR}) coverage of the undiminished shock pressure, P_S.

First of all in Reference 8, it is shown for a flat faced projectile that the critical angle of yaw is:

$$\phi_{CR} = \mathrm{ARCSIN}\,(V_I / U_{sp}) \qquad (2)$$

The critical yaw angle , ϕ_{CR}, is depicted in Figure 3 which is similar to Figure 10b of Reference 8. For angles less than ϕ_{CR}, the magnitude and duration of the shock pressure are practically the same as an unyawed projectile. For yaw angles greater than ϕ_{CR}, the full Hugoniot shock pressure exists only at the point of contact.

In addition, it is indicated in Reference 8 that Equation 2 also defines the critical angle for the full Hugoniot shock pressure duration and affected area of a curved surface impacting a flat target. This is illustrated in Figure 4 for a hemispherical nose shape. Figure 4 is similar to Figure 11 of Reference 8.

The angle, ϕ, between the flat target surface and the projectile curved surface changes and increases as penetration increases. When ϕ exceeds ϕ_{CR}, a rarefaction (tensile) wave forms at the projectile surface/target surface edge contact point and propagates back into the shocked region. This reduces the Hugoniot pressure duration and its areal coverage.

In Section II, it was shown how the effective or equivalent diameter (D_{FNEQ}) of HN projectiles was determined from experimental data. Figure 5 illustrates the geometrical relationship between D_{FNEQ} and D_{HN}. They are related to an angle, ϕ_{EQ}, which is:

$$\phi_{EQ} = \text{ARCSIN}\,(D_{FNEQ}/D_{HN}) \tag{3}$$

So far, two angles, ϕ_{CR} and ϕ_{EQ}, have been defined for the hemispherical shape via Equations 2 and 3, respectively. To ascertain whether these angles were equal or related, they were computed and compared as follows.

The angle ϕ_{CR} was computed for all the HN and spherical projectile impact data discussed in Section II. The results are listed in Table 2 and plotted versus V_I in Figure 6. Figure 7 illustrates V_I/U_{SP} plotted versus V_I. See the Appendix for additional information regarding the computation of U_{SP} and P_S. These computations took account of the Hugoniot Elastic Limit (HEL) and 130 KBAR transition point that occurs in iron and mild steel [9 and 10].

The equivalent flat nose diameters (D_{FNEQ}) for each of the HN and spherical projectiles were determined graphically from the experimental data plots as illustrated in Figures 1 and 2. For a given V_I, the shock pressure (P_S) must be the same for both FN and HN or spherical projectiles. When D_{FNEQ} is found, then ϕ_{EQ} is computed via Equation 3. This information is listed in Table 1 and depicted in Figures 6 and 7 as a function of V_I.

The comparative information in Figures 6 and 7 reveals that essentially:

$$\phi_{CR} = \phi_{EQ} \tag{4}$$

or

$$\frac{D_{FNEQ}}{D_{HN}} = \frac{V_I}{U_{SP}} \tag{5}$$

In Figure 8, D_{FNEQ}/D_{HN} is plotted versus V_I/U_{SP} and the comparison is essentially one–to–one. Thus practically, for the limited amount available:

$$D_{FNEQ} = \left(\frac{V_I}{U_{SP}}\right) D_{HN} \tag{1}$$

$$= \text{a function of } V_I$$

Although the magnitudes of ϕ_{CR}, ϕ_{EQ}, or D_{FNEQ}/D_{HN}, V_I/U_{SP} still compare favorably for PBX–9404 at $V_I = 1.95$ km/sec or $V_I/U_{SP} = 0.385$ the data trend is different. There is a crossover of ϕ_{EQ} and D_{FNEQ}/D_{HN} from being slightly greater than ϕ_{CR} and V_I/U_{SP}, respectively to being somewhat smaller (Figs. 6, 7, and 8). This may be caused by the projectile material behavior since P_S is greater than 130 Kbars, which is a phase change point and for iron and mild steels.

Note that in Table 2, the second wave shock velocity at the 130 Kbar point was employed in Equation 2 rather than the slower third wave velocity. The results at $V_I = 1.70$ km/sec may also be influenced by this projectile material phase change. Some additional experimental data at higher V_I conditions and smaller projectile diameters are needed to more completely define the data trend. Systematic testing with other projectile materials such as tungsten alloys (which are commonly used in severe impact applications) is needed for a variety of important explosives.

It was noted in Section I that if D_{FNEQ} equivalence is a valid concept, then there should be good agreement with various FN projectile data correlation parameters such as the widely used explosive sensitivity parameter ($V_I \sqrt{D}$ = constant) which was first suggested by Dr. Manfred Held in 1968 [11, 12, and 13]. The Held constant differs for different explosives. In Reference 1, Appendix E, this sensitivity parameter is evaluated for PBX–9404 and COMP–B for the same FN projectile data which is shown in Figures 1 and 2, respectively.

The flat nose sensitivity factor, $V_I \sqrt{D}$, for PBX–9404 and COMP–B is tabulated in Reference 1 and is plotted versus V_I in Figures 9 and 10, respectively of the present report. Also shown in these Figures are the results for $V_I \sqrt{D_{FNEQ}}$ for the HN and the spherical projectiles considered in this report. The tabulated values are listed in Tables 2 and 3.

Note that in Tables 3 and 4 D_{FNEQ} is not the experimental value shown in Table 1. D_{FNEQ} is computed via Equation 1, such as could or would be done in an engineering application to predict detonation if experimental data were not available. These $V_I \sqrt{D_{FNEQ}}$ results compare reasonably well with the FN projectile parameter, $V_I \sqrt{D_{FN}}$.

It is believed that the equivalent flat nose diameter concept could also be applied to correlate (via the Held parameter as described above) some of the shaped charge jet/explosive detonation data. However, the jet tip shape can vary a considerable amount [14] so that a complete correlation may not be possible. As time and circumstances permit, an attempt to correlate the shaped charge jet /detonation data via the $V_I \sqrt{D_{FNEQ}}$ parameter will be made.

IV. CONCLUSIONS

A small sample of experimental data have been used to derive what appears to be a valid geometric equivalence relationship suitable for detonation predictive purposes in those cases involving flat nosed and hemispherical projectiles. The HN shape is important from a practical point of view. Many "Sharp–pointed" projectiles have a small hemispherical tip. Also blunt or flat projectiles erode during penetration of armor and/or shields, and the resulting shape is approximately hemispherical. If an energetic material is being shielded, Equation 1 and the Held sensitivity coefficient can be employed in detonation prediction analyses. Also the equivalent flat nosed diameter concept may be applicable to shaped charge jets as mentioned in Section III.

V. RECOMMENDATIONS

The data and analysis reported here suggest that detonation data acquired using impact of Flat nosed projectiles on bare explosives can be used to establish detonation criteria for projectiles of other symmetric shapes. Additional testing such as reported in References 5, 6, and 7 is required to validate the postulated geometric equivalence definition for flat nosed and hemispherical tipped projectiles.

Table 1. Experimental Results for D_{FNEQ} and ϕ_{EQ}

Explosive ~	D_{HN} cm	D_{FNEQ} cm	D_{FNEQ}/D_{HN} ~	ϕ_{EQ} Deg.
PBX–9404	0.4445	0.150	0.3375	19.72
	0.5080	0.175	0.3445	20.15
	0.6300	0.200	0.3175	18.51
[5]	1.1430	0.308	0.2695	15.63
	1.2700	0.330	0.2598	15.06
	1.7780	0.405	0.2278	13.17
PBX–9404 [6]	1.300 (Spherical)	0.320	0.2461	14.25
COMP–B [6]	1.300 (Spherical)	(0.420)*	0.3231	18.85

* See Text, Section II

Table 2. Computed Results for U_{SP} and ϕ_{CR}

Explosive ~	D_{HN} cm	V_I km/sec	U_{SP} km/sec	U_{PP} km/sec	P_S Kbars	U_{SEX} km/sec	U_{PEX} km/sec	V_I/U_{SP} ~	ϕ_{CR} Deg
PBX–9404	0.4445	1.95	5.069*	0.470	166.9	6.120	1.480	0.3847	22.62
	0.5080	1.70	5.069*	0.375	140.0	5.736	1.325	0.3354	19.60
	0.6300	1.53	5.037	0.306	123.7	5.485	1.224	0.3037	17.68
[5]	1.1430	1.21	4.927	0.223	89.0	4.898	0.987	0.2456	14.22
	1.2700	1.16	4.910	0.211	84.0	4.804	0.949	0.2363	13.66
	1.7780	1.04	4.872	0.182	72.4	4.578	0.858	0.2135	12.33
PBX–9404 [6]	1.300 Spherical	1.14	4.900	0.203	82.0	4.773	0.937	0.2326	13.45
COMP–B [6]	1.300 Spherical	1.75	5.062	0.325	129.1	5.33	1.425	0.3457	20.22

*Iron Shock Velocity at 130 Kbar Transition Point

Table 3. The Held Explosive Sensitivity Factor, $V_I\sqrt{D_{FNEQ}}$, for Hemispherical Projectiles Striking PBX–9404

V_I	V_I/U_{SP}	D_{HN}	D_{FNEQ} ($V_I/U_{SP}{*}D_{HN}$)	$\sqrt{D_{FNEQ}}$	$V_I\sqrt{D_{FNEQ}}$	$V_I^2D_{FNEQ}$
mm/μ–sec	~	mm	mm	$mm^{1/2}$	$mm^{3/2}$/μ–sec	mm^3/μ–sec^2
1.95	0.3847	4.445	1.710	1.308	2.550	6.502
1.70	0.3354	5.080	1.704	1.305	2.219	4.92.4
1.53	0.3037	6.300	1.913	1.383	2.116	4.479
1.21	0.2456	11.430	2.807	1.675	2.027	4.110
1.16	0.2363	12.700	3.001	1.732	2.010	4.038
1.04	0.2135	17.780	3.796	1.948	2.026	4.106
1.14	0.2326	13.00 (spherical projectile)	3.024	1.739	1.982	3.930 spherical

Table 4. The Held Explosive Sensitivity Factor, $V_I\sqrt{D_{FNEQ}}$, for a Spherical Projectile Striking COMP–B

V_I	V_I/U_{SP}	D_S	D_{FNEQ} ($V_I/U_{SP}{*}D_{HN}$)	$\sqrt{D_{FNEQ}}$	$V_I\sqrt{D_{FNEQ}}$	$V_I^2D_{FNEQ}$
mm/μ–sec	~	mm	mm	$mm^{1/2}$	$mm^{3/2}$/μ–sec	mm^3/μ–sec^2
1.75	0.3457	13.00	4.494	2.120	3.71	13.76

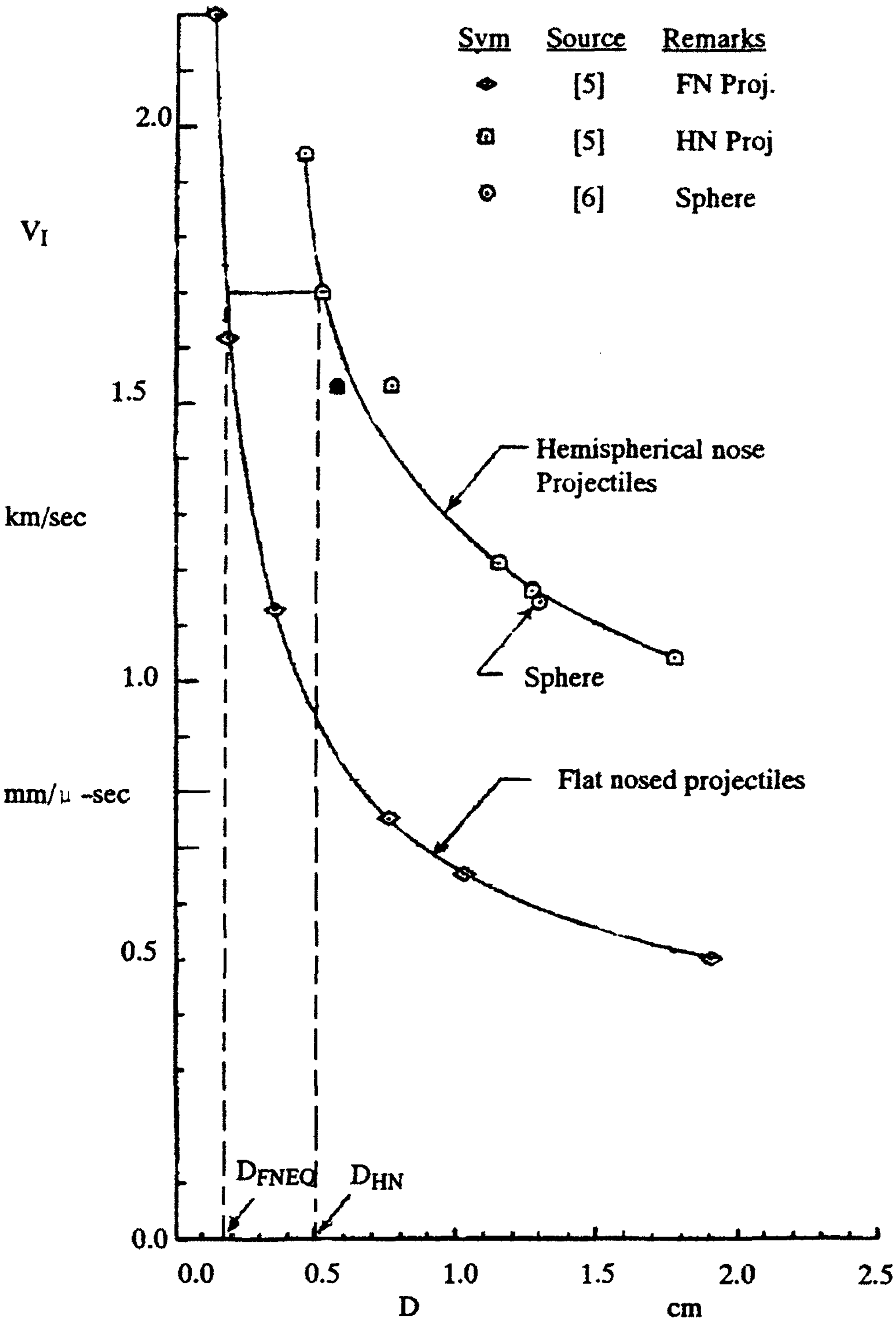


Figure 1. Impact Velocity Required to Detonate PBX–9404 for Different Projectile Diameters

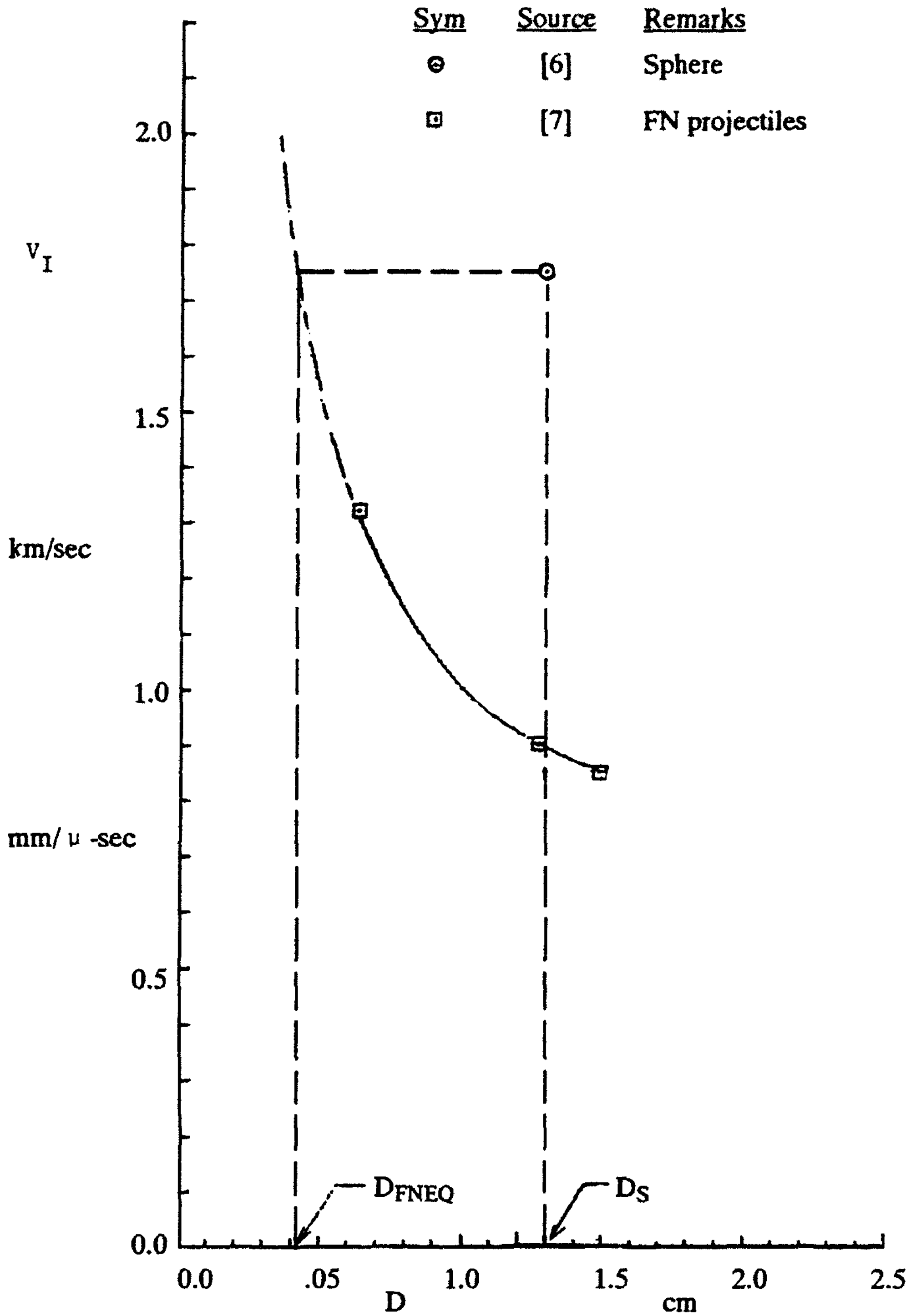


Figure 2. Impact Velocity Required to Detonate COMP–B for Different Projectile Diameters

$$\sin\phi_{CR} = \frac{V_I}{U_{SP}}$$

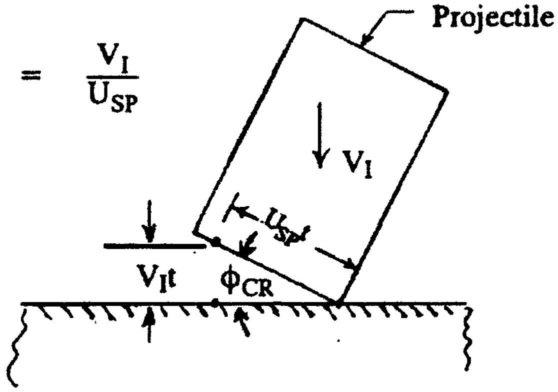
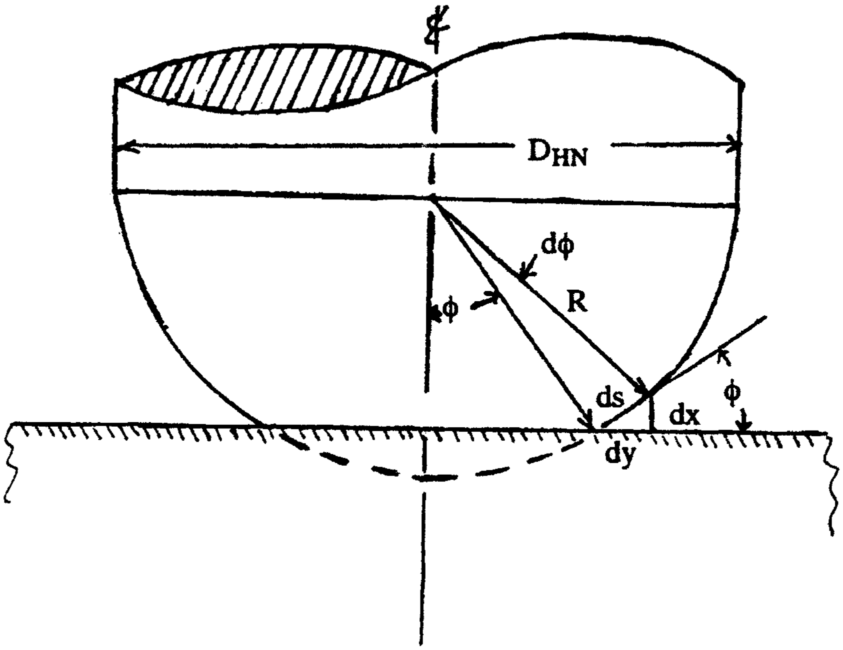


Figure 3. Critical Contact Conditions for a Flat Nose Projectile Impacting a Flat Target



$$U_{SP}\,dt = ds = Rd\phi$$

$$V_I\,dt = dx = ds\sin\phi CR = Rd\phi\sin\phi_{CR}$$

$$\frac{V_I}{U_{SP}} = \frac{dx}{ds} = \frac{Rd\phi}{Rd\phi}\sin\phi_{CR} = \sin\phi_{CR}$$

Figure 4. Critical Contact Conditions for a Hemispherical Nose Projectile Impacting a Flat Target

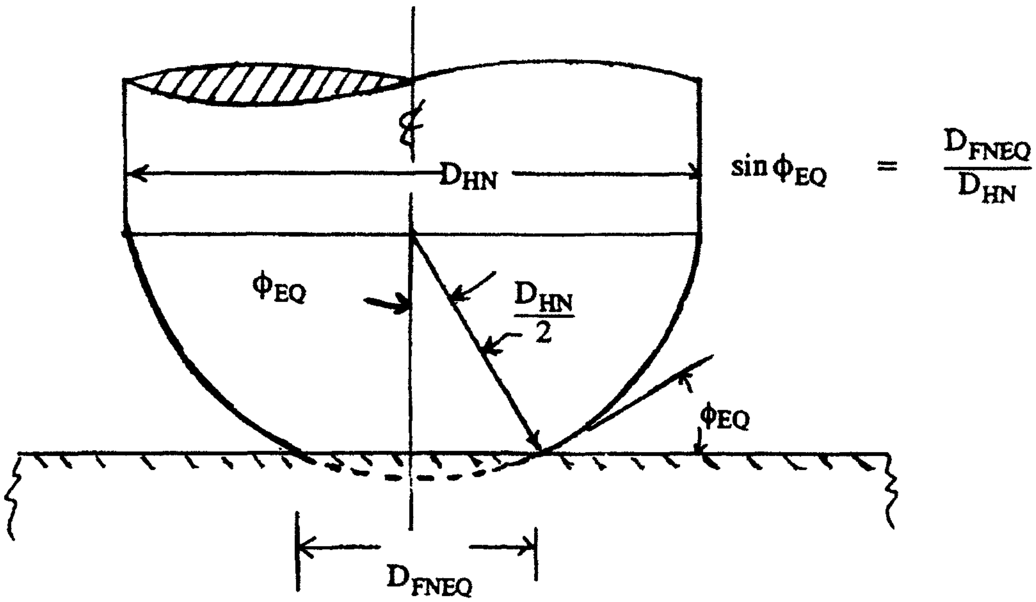


Figure 5. Schematic of Equavalent Flat Nose Diameter (D_{FNEQ}) for Hemispherical Projectiles

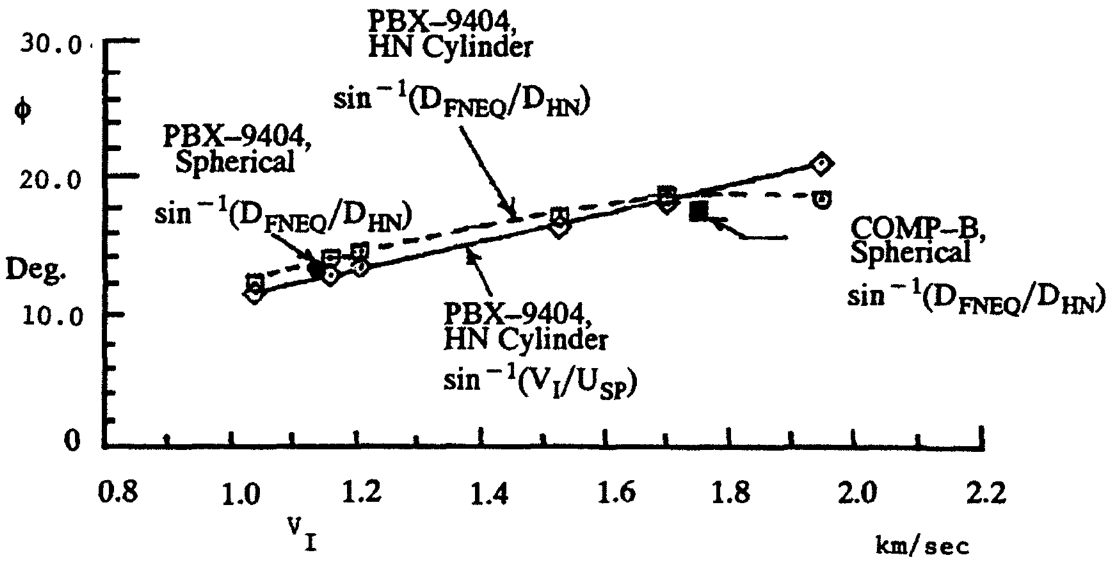


Figure 6. ϕ Versus V_I

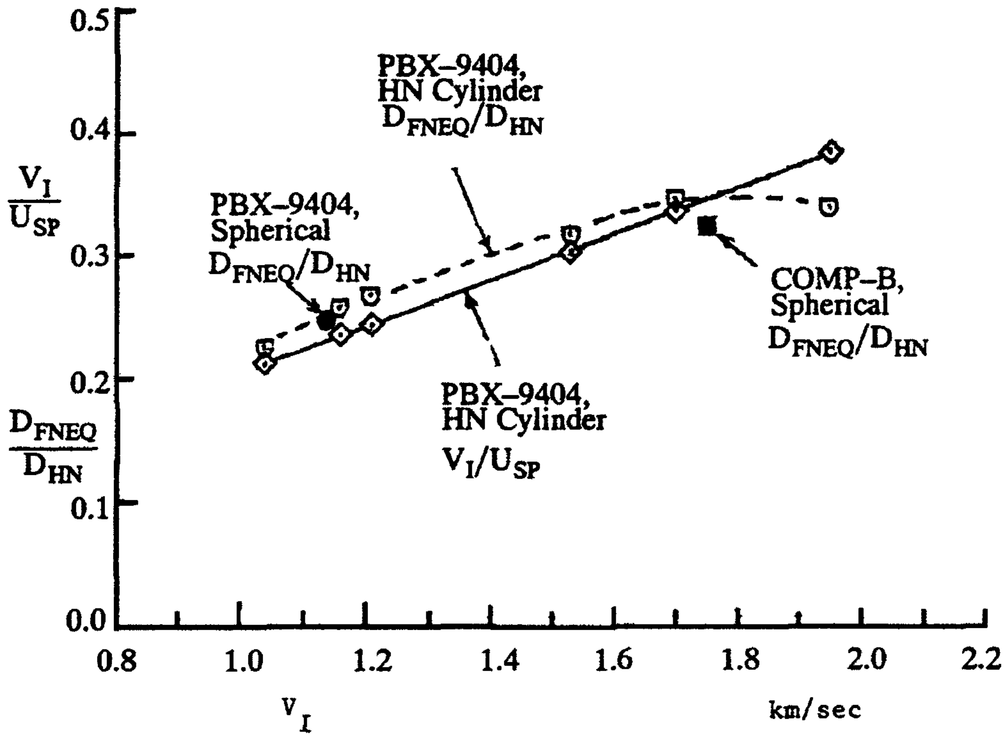


Figure 7. V_I/U_{SP} and D_{FNEQ}/D_{HN} Versus V_I

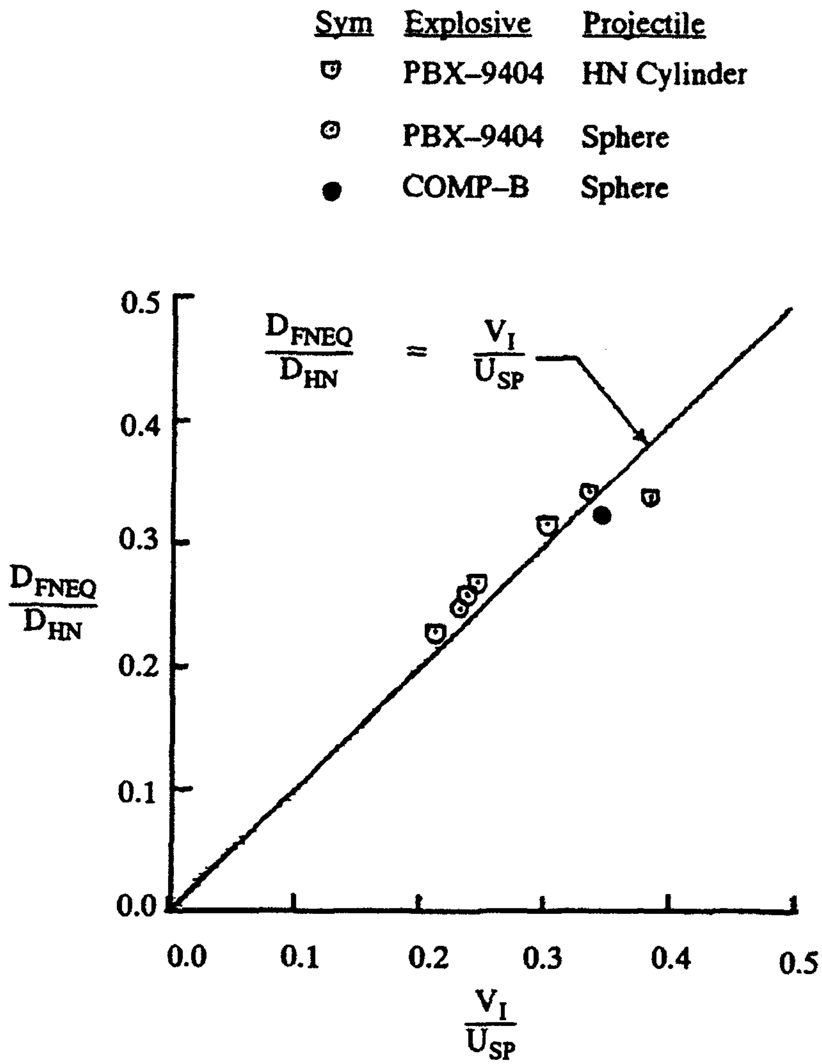


Figure 8. D_{FNEQ}/D_{HN} *Versus* V_I/U_{SP}

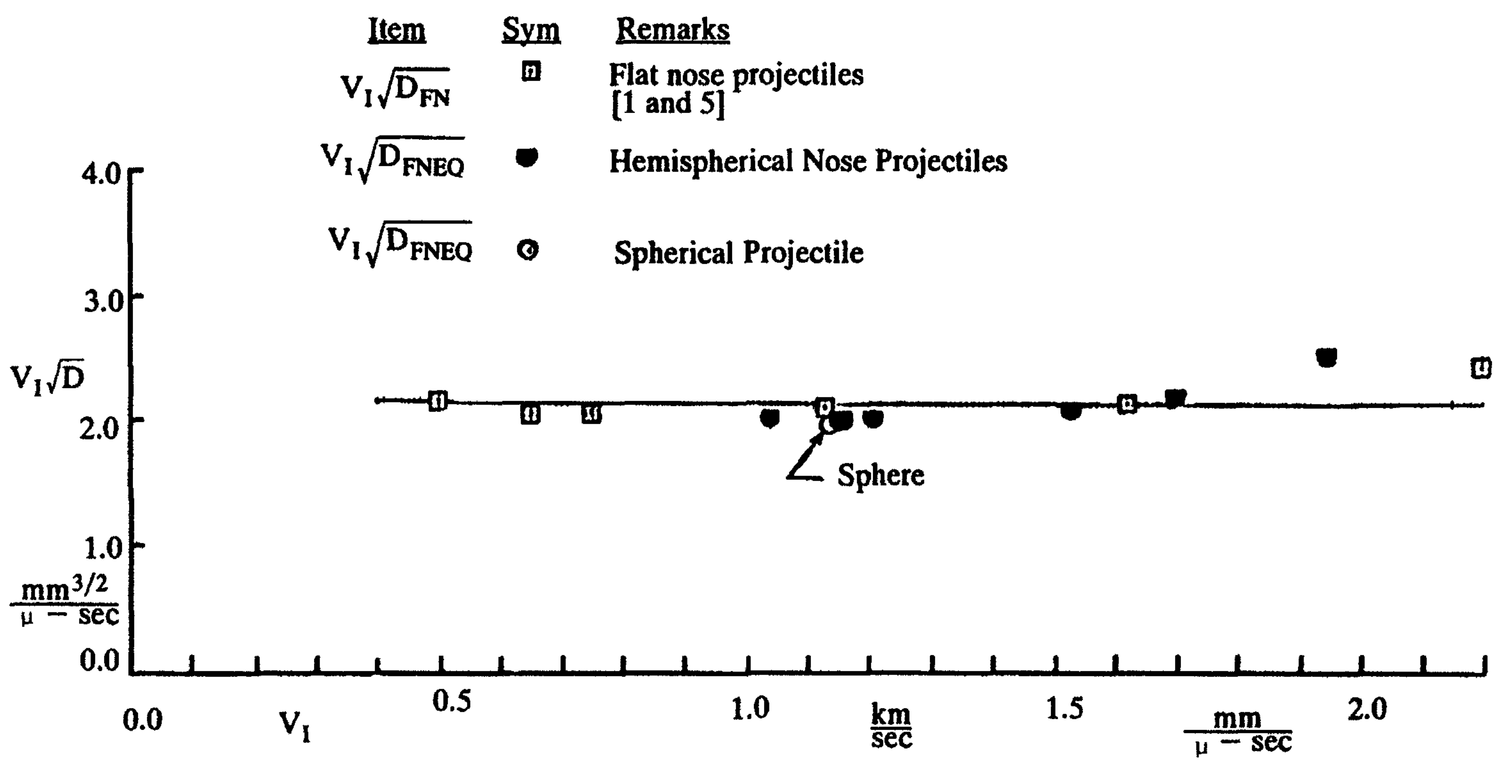


Figure 9. The Held Parameter, $V_I\sqrt{D}$, *Versus* V_I *for PBX–9404*

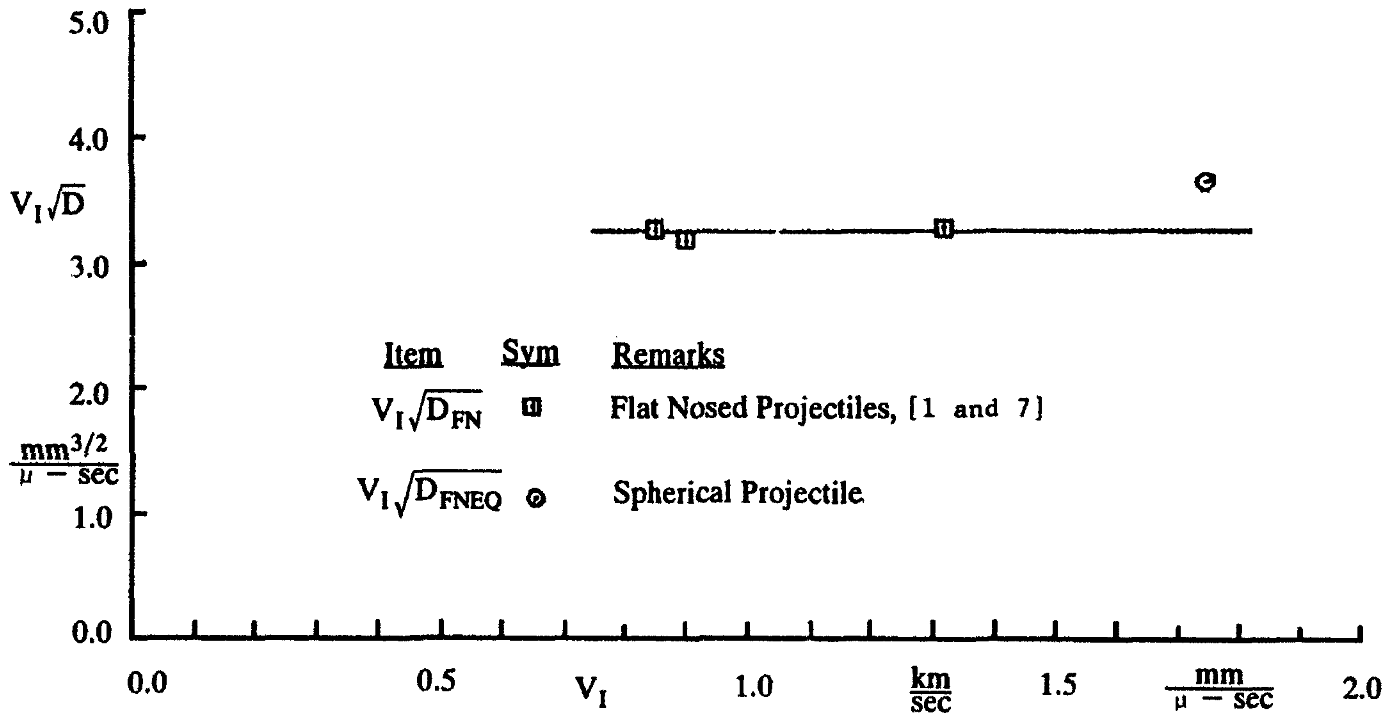


Figure 10. The Held Parameter, $V_I\sqrt{D}$, *Versus* V_I *for COMP–B*

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APPENDIX
IMPACT SHOCK VARIABLE RELATIONSHIPS AND BASIC DATA

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IMPACT SHOCK VARIABLE RELATIONSHIPS AND BASIC DATA

Iron and some steels, under moderate impact shock loading below 130 Kbars, exhibit a two wave structure where the first one is essentially an elastic wave followed by a slower plastic wave front. The elastic wave is generated under these conditions is called the Hugonoit Elastic Limit (HEL) to distinguish it from a dynamic elastic limit which could occur under less severe loading conditions [9]. The double wave structure requires that computations for pressures and densities be performed via the following equations.

The pressure behind the HEL wave is:

$$P_{HEL} = \rho_o C_L U_{PHEL} \tag{A-1}$$

The density behind the HEL wave is:

$$\varrho_{HEL} = \varrho_o \left(\frac{C_L}{C_L - U_{pHEL}} \right) \tag{A-2}$$

$$\approx \varrho_o \tag{A-3}$$

Equation A–3 is a good aproximation because C_L, the longitudinal wave velocity, is much larger than U_{PHEL} so that $C_L/(C_L - U_{PHEL}) \approx 1.0$. To a good approximation, since U_s, is generally much larger than U_{PHEL}, the shock front pressure corresponding to the paritcle velocity U_P is:

$$P_S = P_{HEL}\ U_S\ (U_P - U_{PHEL}) + P_{HEL} \tag{A-4}$$

Experimentally, it has been found for many materials, that the shock velocity U_S, is a linear function of the particle of velocity, U_P. This relation is commonly represented by:

$$U_S = C_o + S\,U_P \tag{A-5}$$

Where C_0 and S are experimentally determined constants. These constants for iron (or mild steel), PBX–9404, and COMP–B are given in Table A–1. For steel the HEL wave velocity, particle velocity, and pressure values employed were taken from Reference 15. They are:

C_L = 6.04 km/sec
U_{PHEL} = 0.0288 km/sec
P_{HEL} = 13.6 KBARS

In Appendix A of Reference 1, it was shown how to analytically compute the initial contact particle velocities of colliding materials. In Reference 1, the effect of an HEL precursor wave was not considered. However, in Reference 16, the HEL effect was included and this procedure was employed in the present analysis for shock pressures less than or equal to 130 Kbars where a phase transition occurs in the iron or mild steel projectiles. Above P_S = 130 Kbars three waves exist (one elastic and two plastic) until the plastic wave velocity (U_S) exceeds the elastic wave velocity (C_L). This one–wave situation occurs at very high impact velocities (V_I). None of the experimental data analyzed in the present investigation were in this one–wave region, but three data points were in the 3–wave region or very close to it. The initial particle velocities for these three data points were obtained by the graphical procedure suggested in Reference 1. Table 2 in the main body of this report, contains both the analytical and computed results. Both procedures depend on following expression which is valid at the contact interface of the projectile (P) and explosive (EX).

$$V_I = U_{PP} + U_{PEX} \tag{A-6}$$

When the particle velocities are known, then U_S and P_S can be found from the appropriate relations (A–5 and A–4, respectively).

Table A–1
Impact Shocked Material Information

Material ~	ρ_0 Grams/cm^3	C_0 km/sec	S ~	Source ~	Comments ~
Iron or	7.84	4.63	1.33	[17, 18]	$P_S \leq 130$ KBARS
mild steel	7.84	1.10	4.22	[10]	$P_S > 130$ KBARS
PBX–9404	1.84	2.45	2.48	[19, 20]	
Comp–B	1.70	2.95	1.67	[21]	S was modified from 1.58 to 1.67

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